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**TITLE:** ELECTRICAL DESIGN OF A HIGH DENSITY AIR-CORE  
REVERSED-FIELD PINCH "ZTP"

**AUTHOR(S):** William A. Reass, Jimmy G. Melton and Robert F. Gribble

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**Los Alamos** Los Alamos National Laboratory  
Los Alamos, New Mexico 87545

# ELECTRICAL DESIGN OF A HIGH CURRENT DENSITY AIR-CORE REVERSED-FIELD PINCH "ZTP"\*

W. A. Reass, J. G. Melton, and R. F. Gribble  
Los Alamos National Laboratory  
Los Alamos, New Mexico 87545

## ABSTRACT

This paper describes the electrical design of a small, high current density ( $10 \text{ MA/m}^2$ ) toroidal reversed-field Z-Pinch (RFP) presently being constructed at Los Alamos.

Special purpose magnetic field programs were used to calculate self and mutual inductances for the poloidal field windings. The network analysis program MINI-SCEPTRE was then used to predict plasma current, including the interaction between toroidal and poloidal field circuits, as described by the Bessel function model for RFP's.

Using those programs, coil geometry was obtained for minimal field errors and the pulse power systems were optimized to minimize equilibrium control power. Results of computer modeling and implementation of the electrical circuits are presented.

## INTRODUCTION

ZT-P is a small, multipurpose, reversed-field pinch (RFP) experiment presently being constructed at LANL. It is intended to be a versatile experimental facility which can provide answers to several outstanding questions concerning present RFP operations and the design of future RFP experiments. It was designed to serve several specific purposes: (1) to provide an engineering and physics test of an air-core RFP device, (2) to investigate RFP operation at high current density ( $10 \text{ MA/m}^2$ ) relevant to the compact RFP reactor concept, (3) to provide an experiment designed to have very low magnetic field errors, allowing controlled field error experiments to be performed, (4) to investigate divertor-like magnetic field configurations, and (5) to investigate different configurations of the conducting shell, including the possibility of operating without a conducting shell.

This paper discusses primarily the electrical design of ZT-P. The design of the poloidal field system is discussed first in order to establish the method adopted for producing the correct equilibrium fields. Then the circuit simulations to verify the method are discussed and the calculated results are presented. Finally, the final design of the electrical systems for the machine is presented.

## POLOIDAL FIELD COIL SYSTEM

The poloidal field (PF) coil set is composed of two sets of windings, shown in Fig. 1. The magnetizing (M) winding provides the poloidal flux swing to drive the plasma current. It is composed of two sets of windings with 40 turns each, symmetrically arranged with respect to the machine mid-plane, to allow series or parallel connection of the windings. The individual coils are positioned to direct the return flux from the central solenoid around the region occupied by the plasma, producing minimum stray field in the plasma region. These windings are the inner set of solenoidal coils shown in Fig. 1.

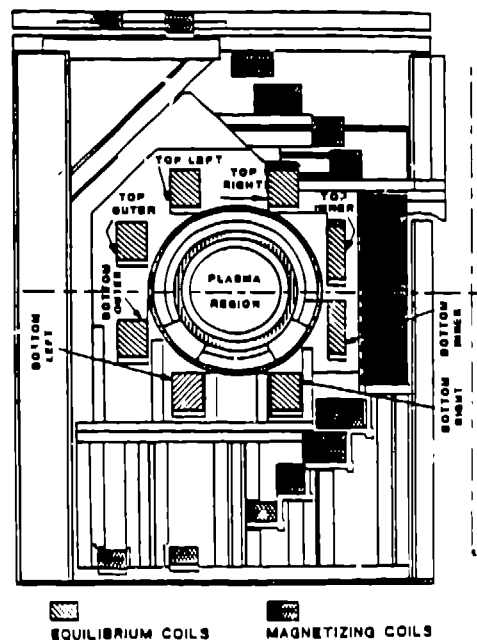


Figure 1. Arrangement of Poloidal Field Coils.

The equilibrium (EF) coil set produces a flux surface at the liner which deviates less than  $\pm 2.7 \text{ mm}$  from circular. These coils each have several taps such that the turns ratio can easily be changed. There are no separate vertical field or horizontal field windings. Rather, the vertical field required for equilibrium and the field indexing required for vertical stability are produced by distributing the currents in the EF-coils via external equilibrium power supplies. The EF-coils are cross-connected as shown in Fig. 2. Computer simulations have shown that the correct vertical field and field index can be achieved with the use of only two external power supplies if this coil cross-connection is used.

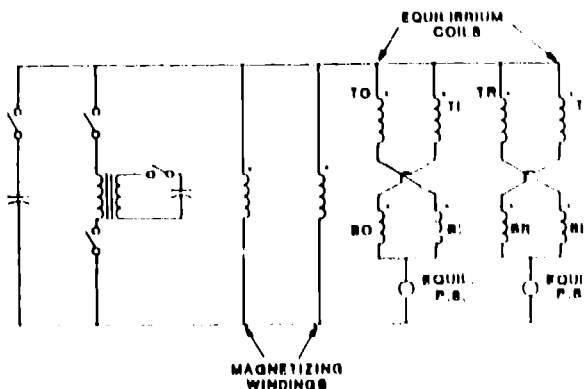


Figure 2. Poloidal Field Circuit, Showing Cross-connection of Equilibrium Coils.

\* Work performed under the auspices of US DOE.

COMPUTER VERIFICATION OF CIRCUIT DESIGN

The network program MINI-SCEPTRE as implemented on the MF6CC computer is unable to handle mutual inductances in circuits. In order to circumvent this difficulty and still use MINI-SCEPTRE instead of the full version of SCEPTRE (which we have found runs much slower), the coil currents were represented as current sources and the inverted inductance matrix was used in the differential equation solving feature of MINI-SCEPTRE to solve for the coil currents. In Fig. 3, showing the poloidal field equivalent circuit, the coil currents are represented by the current sources ( $J_n$ ).  $J_1$  is the current in the magnetizing winding,  $J_2$  and  $J_3$  are the currents in the two branches of the EF-coils, and  $J_T$  is the plasma current. The plasma resistance is represented as a time varying value dependent on the current density, as scaled from ZT-60M. Coupling between the poloidal and toroidal circuits is accomplished via the Culham coupled model for RFP's.

The diagram illustrates the electron gun and plasma column. It features a series of vertical electrodes: RRO1, RSCF, LBI, LBF, RB1, RB2, RB, R1 COIL, R2 COIL, R3 COIL, PLASMA R, and LINER R. A central vertical line represents the electron beam path. A dashed box encloses the PLASMA R and LINER R sections. Labels include 'USTR' at the bottom left, 'P.B.V' and 'P.B.S' at the bottom, and 'U1' through 'U4' indicating various voltages or potentials.

distribution of currents in the EF-coils. The difference between the two fields is used to excite a feedback circuit which drives the equilibrium power supplies. The program then calculates the power being output by the power supplies.

A line graph showing the magnetic field in gauss (G) on the y-axis (0 to 8) versus time in milliseconds (ms) on the x-axis (0 to 3). Four curves are plotted, all starting at 0 and rising sharply to a plateau within the first millisecond. The curves are:
 

- OUTER & COIL 1 (GA)**: Solid line, plateaus at approximately 6.2 G.
- REG'D OUTER & COIL 1 (GA)**: Dashed line, plateaus at approximately 6.8 G.
- INNER & COIL 1 (GA)**: Dotted line, plateaus at approximately 7.2 G.
- REG'D INNER & COIL 1 (GA)**: Dash-dot line, plateaus at approximately 7.8 G.

 The curves remain relatively stable after the initial rise, with a slight dip around 2.5 ms before returning to the plateau level.

Graph showing the relationship between Vertical Field (G) and Debye Wall Index over time (Milliseconds).

The X-axis represents time in Milliseconds, ranging from 0 to 4.

The left Y-axis represents Vertical Field (G), ranging from 0.00 to 0.25.

The right Y-axis represents Debye Wall Index, ranging from 0.0 to 1.0.

Legend:

- Solid line: VERTICAL FIELD (G)
- Dashed line: DEBYE WALL INDEX

Approximate data points extracted from the graph:

Time (Milliseconds)	Vertical Field (G)	Debye Wall Index
0.0	0.00	0.00
0.2	0.00	0.42
0.5	0.22	0.42
1.0	0.24	0.42
2.0	0.24	0.42
3.0	0.23	0.42
4.0	0.22	0.42

Figures 6 and 7 show a comparison between required and actual FF-coil currents and vertical field for a well matched condition, and Fig. 8 shows the power output required from the equilibrium supplies. During the setting-up phase, the power supplies must supply a combined peak of 23-MW, but during the flat-top phase (after 1 ms), they are absorbing about 4 MW from the power crowbar bank.

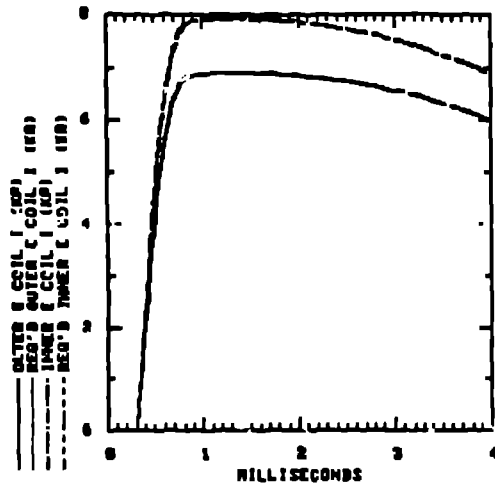


Figure 6. EF-Coil Currents - (Matched Case) Comparison of Actual Currents and Currents Required to Produce Equilibrium Vertical Field.

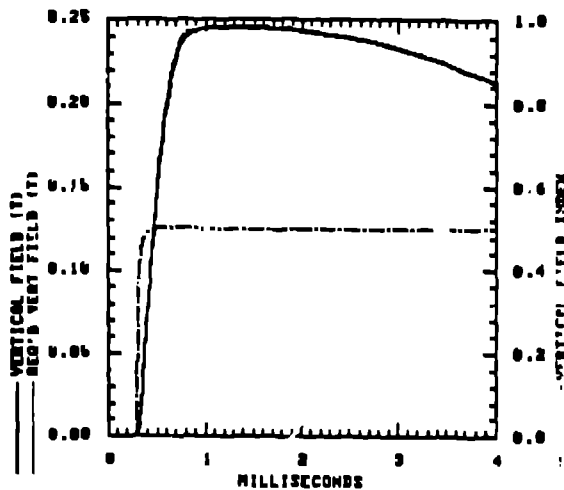


Figure 7. Vertical Field and Field Index - (Matched Case) Comparison of Actual Field and Field Required for Equilibrium.

#### ELECTRICAL CIRCUIT DESCRIPTION

The electrical circuits to drive ZT-P are shown in Figs. 7 and 10. The main energy storage is in capacitor banks, which are switched through ignitrons. The energy to flat-top the current is supplied from power crowbar capacitor banks, coupled into the main circuits through low-inductance, low-resistance transformers. Two "equilibrium" power supplies distribute the current in the EF-coils to provide the vertical field.

The poloidal field circuit is shown in Fig. 9. The main (start) capacitor banks consist of four sections, each with twelve 170  $\mu$ F 10-kV capacitors, connected to operate at  $\pm 20$ -kV with respect to ground. The power crowbar capacitor bank consists of 43 each 170  $\mu$ F capacitors operated at  $\pm 10$ -kV with respect to ground. Switching is accomplished by size-D ignitrons. All capacitor banks contain small damping resistors to provide a damped waveform in the event of a system dump and to limit fault currents.

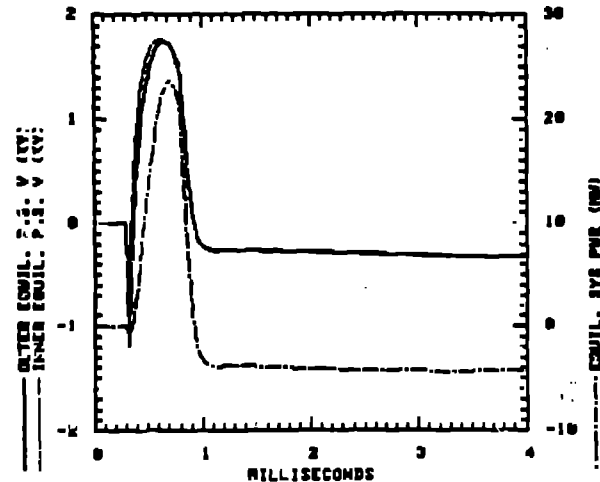


Figure 8. Output of Equilibrium Power Supplies for Matched case.

The power crowbar transformer in the poloidal field circuit requires 6 V-s flux swing and a turns ratio of 4:1 to match the 10-kV PCB bank to the primary circuit. A core with .376 V-s bipolar flux swing was available and was selected, requiring 72 primary turns and 18 secondary turns.

Protective end-of-shot-dump (EOSD) ignitrons (size-D) are provided to dump the power crowbar energy in the event of plasma termination or failure to achieve plasma breakdown. Failure to do so could result in overstressing the PF coils. They may also be used to terminate a normal shot, by ramping the current gradually to zero. The EOSD circuits will have resistance values small enough to effectively shunt current from the EF-coils and large enough to damp oscillations.

The toroidal field circuit is shown in Fig. 10. The main capacitor bank consists of 24 each 60  $\mu$ F 10-kV capacitors, that are switched by back-to-back ignitrons. 0.8-ohm resistors on each capacitor reduce ringing when the crowbar ignitron is closed. The power crowbar bank is a single 60  $\mu$ F capacitor, coupled through the 80:1 power crowbar transformer. The transformer core has 0.128 V-s bipolar, with 240 primary turns and 3 secondary turns. This transformer must have very low secondary leakage inductance.

In both circuits coaxial cables (17/14 HR) provide the interconnections between components. The use of coaxial cables allows considerable flexibility in locating the components and in accommodating future circuit changes.

The design of the equilibrium feedback system is given in Fig. 11. Flux and position sensors provide active feedback to the error and loop compensation amplifiers located at ground potential. The equilibrium power supplies are transformer-coupled hard-tube amplifiers, with an output stage consisting of six parallel 6L8618 magnetic beam focus triodes in a grounded cathode configuration. Each tube will have a plate current of about 170 A, which is supplied by a common 20 kV 255  $\mu$ F (51 KJ) capacitor bank. As each equilibrium coil requires a boost of about 9%, the bank voltage will drop about 2 KV.

To drive the ML8618's, a fiber-optic controlled hot-deck amplifier with a single 3CX20,000A3 output tube is used. Solid state circuitry is direct-coupled to the grid, with "DC" fiber-optic links providing voltage isolation.

ZT-P is presently under construction, following the design described in this paper. It is scheduled to begin operation possibly as early as June, 1984.

## REFERENCES

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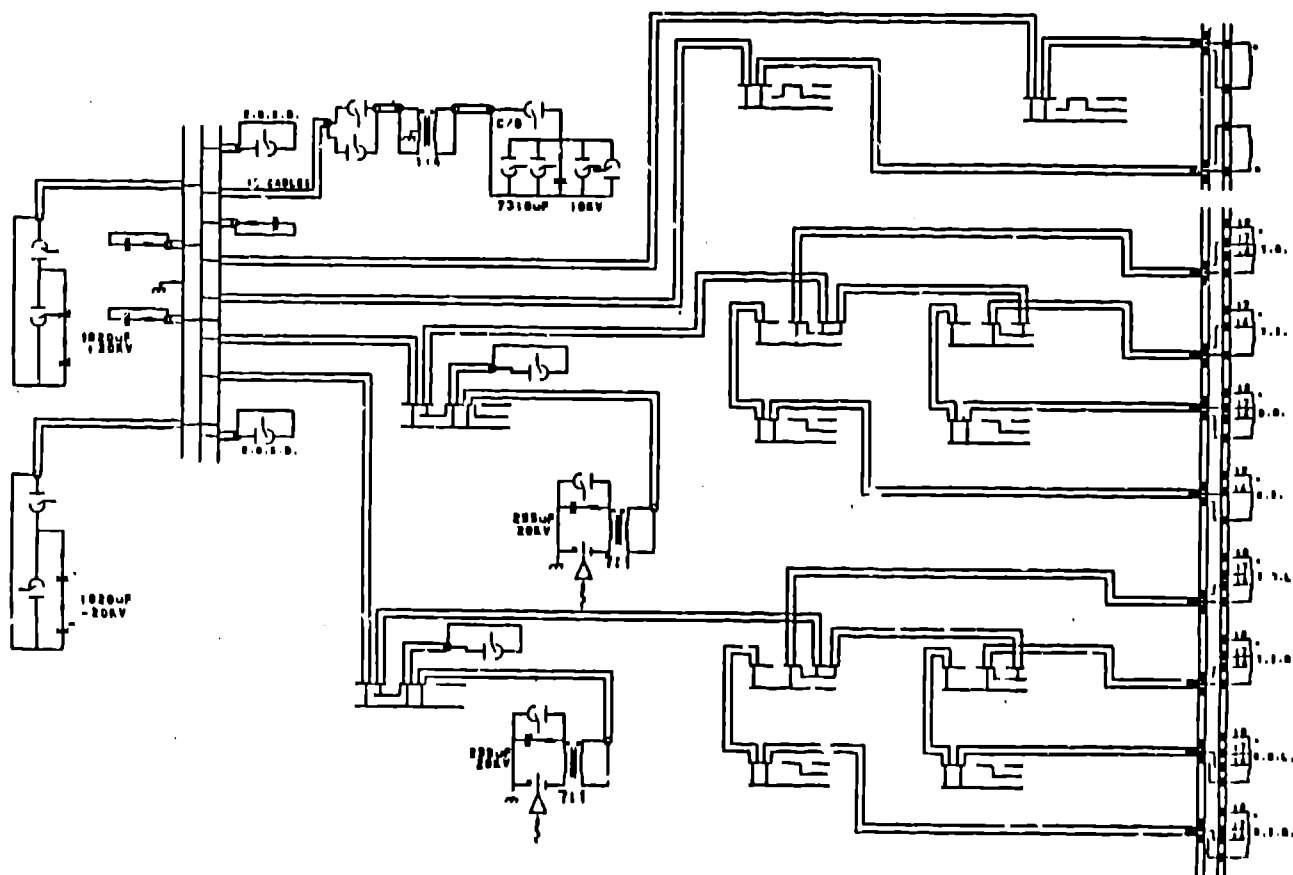


Figure 11. Circuit Diagram of Equilibrium Power Supplies.